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Final Report: Piezoelectric Resonance Defined High Performance Sensors and Modulators

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5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
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6. AUTHORS
Ruyan Guo (PI), Amar Bhalla (CoPI, UTSA), Michael Miller (Collaborating CoPI, SwRI)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Texas at San Antonio
One UTSA Circle

San Antonio, TX 78249 -1644

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Electromechanical resonance of piezoelectric crystals has been shown to have substantial influence on their electrooptic interactions and is of significant interests for a wide range of public or DoD-applications. This project explored the mechanisms of enhanced electro-optic interactions at high frequencies, established essential understandings on lattice-polarization process by successfully conducted a family of experimental measurements combined with computational modeling. Ferroelectric crystals such as PMN-PT,PZN-PT, LiNbO3 were studied. Electro-optic, mechanical vibration and admittance experiments verified the high degree of coupling available as a

15. SUBJECT TERMS
piezoelectric resonators, electrooptics, microwave, sensors, modulators, PMN-PT, PZN-PT, LiNbO3, THz modulator

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Ruyan Guo
UU	UU	UU	UU		19b. TELEPHONE NUMBER 210-458-7057

Report Title

Final Report: Piezoelectric Resonance Defined High Performance Sensors and Modulators

ABSTRACT

Electromechanical resonance of piezoelectric crystals has been shown to have substantial influence on their electrooptic interactions and is of significant interests for a wide range of public or DoD-applications. This project explored the mechanisms of enhanced electro-optic interactions at high frequencies, established essential understandings on lattice-polarization process by successfully conducted a family of experimental measurements combined with computational modeling. Ferroelectric crystals such as PMN-PT,PZN-PT, LiNbO3 were studied. Electro-optic, mechanical vibration and admittance experiments verified the high degree of coupling available as a result of synchronized crystal vibration. High frequency vibrometry showed that piezoelectric resonance induced strain continues to have influences over the optical signal propagation despite of its apparent mechanical clamping. Multiphysics COMSOL FEA models were constructed to simulate the crystal vibration, admittance spectrum, linear electro-optic effect, photoelastic effect, and optical wave propagation. These numerical models complemented the observed experimental results and provided new insights into the dynamic nature of the induced periodic displacement current in a resonating sample. Time domain simulations verified the possibility of broad bandwidth enhancement by AC resonance biasing. The influence of periodic gradient structure on the enhancement of microwave transmission was predicted and validated in terahertz spectroscopy experiments conducted using LiNbO3 single crystals.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
05/24/2016	32.00	Juan P. Tamez, Amar Bhalla, Ruyan Guo. Design and Simulation of 100 kHz and 200 kHz Tri-Phasic PZT Piezoelectric Transducers, Integrated Ferroelectrics, (12 2015): 99. doi: 10.1080/10584587.2015.1102579
05/26/2016	33.00	Moumita Dutta, Md. Shafiqur Rahman, Amar S. Bhalla, Ruyan Guo. Optical and microstructural characterization of multilayer Pb(Zr0.52Ti0.48)O3 thin films correlating ellipsometry and nanoscopy, Journal of Materials Science, (05 2016): 12. doi:
05/30/2016	34.00	Soutik Betal, Moumita Dutta, L. F. Cotica, A. Bhalla, R. Guo. BaTiO3coated CoFe2O4-Core-Shell Magnetoelectric Nanoparticles (CSMEN) characterization, Integrated Ferroelectrics, (12 2015): 225. doi: 10.1080/10584587.2015.1092653
05/30/2016	38.00	Christopher G. Pierce, Jose L. Lopez-Ribot, Amar S. Bhalla, Melissa Montes, Ruyan Guo. Properties of Silver and Copper Nanoparticle Containing Aqueous Suspensions and Evaluation of their In Vitro Activity against Candida albicans and Staphylococcus aureus Biofilms, Journal of Nano Research, (12 2015): 109. doi: 10.4028/www.scientific.net/JNanoR.37.109
05/30/2016	36.00	McIntosh, R., Bhalla, A. S., Guo, R.. Modulating frequency and responsivity of pyroelectric energy converters by finite element analysis, Ferroelectrics, (09 2014): 50. doi:
07/02/2014	10.00	Jun Li, Yang Li, Zhongxiang Zhou, Amar Bhalla, Ruyan Guo. Linear electrooptic coefficient r_51 of tetragonal potassium lithium tantalate niobate K_095Li_005Ta_040Nb_060O_3 single crystal, Optical Materials Express, (11 2013): 0. doi: 10.1364/OME.3.002063
07/02/2014	11.00	Yang Li, Jun Li, Zhongxiang Zhou, Ruyan Guo, Amar S. Bhalla. Electrical properties of lead-free Fe-doped niobium-rich potassium lithium tantalate niobate single crystals, EPL (Europhysics Letters), (12 2013): 0. doi: 10.1209/0295-5075/104/57008
09/08/2013	3.00	Yang Li, Jun Li, Zhongxiang Zhou, Ruyan Guo, Amar S. Bhalla. Low-frequency–dependent electro-optic properties of potassium lithium tantalate niobate single crystals, EPL (Europhysics Letters), (05 2013): 0. doi: 10.1209/0295-5075/102/37004
10/16/2015	19.00	Juan P. Tamez, M. C. Bhardwaj, Amar Bhalla, Ruyan Guo. Simulation and Experimental Studies on Tri-Phasic PZT Piezoelectric Transducer, Ferroelectrics, (12 2014): 0. doi: 10.1080/00150193.2014.974472
10/16/2015	20.00	Jun Li, Yang Li, Zhongxiang Zhou, Ruyan Guo, Amar S. Bhalla. Orientation dependence of dielectric and piezoelectric properties of (K0.95Li0.05) (Ta0.40Nb0.60) O3 single crystal, Ceramics International, (06 2015): 0. doi: 10.1016/j.ceramint.2015.01.064
10/19/2015	30.00	McIntosh, R., Bhalla, A. S., Guo, R.. Modulating Frequency and Responsivity of Pyroelectric Energy Converters by Finite Element Analysis, Ferroelectrics, (10 2014): 50. doi:
TOTAL:	**11**	

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

(Plenary Talk) Guo, R., 12th Mediterranean Workshop and Topical Meeting on Novel Optical Materials and Applications (NOMA 2015), "Ruyan Guo, Robert McIntosh, Amar Bhalla, "ELECTROOPTIC AND MICROWAVE INTERACTIVE PROCESSES IN DENSITY AND POLARIZATION GRADIENT PIEZOELECTRIC RESONATORS"", San Michele, Cetraro, Italy. (June 2015).

Laís Weber Aguiar, Anderson Rodrigues Lima Caires, Eriton Rodrigo Botero, Cláudio Teodoro de Carvalho, Andrelson Wellingotn Rinaldi, Cleiser Thiago Pereira da Silva, Ruyan Guo, Amar S. Bhalla, Evaristo Alexandre Falcao, "Synthesis and Spectroscopic Responses of PVDF Film Doped with Neodymium Compound,". (2015). Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Melissa Montes, Christopher G. Pierce, Jose L Lopez-Ribot, Amar S. Bhalla, Ruyan Guo, "Properties of Silver and Copper Nanoparticle-Containing Aqueous Solutions and Their Anti-Biofilm Effects," (2015)Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Moumita Dutta, Xomalin Peralta, Amar Bhalla, Ruyan Guo, "Low Loss Mixed Oxide Perovskites and their THz Dielectric Spectra," Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Paula N. Oliveira, Denise Alanis, Raquel D. Bini, Daniel M. Silva, Gustavo S. Dias, Ivair A. Santos, Ruyan Guo, Amar S. Bhalla, Luiz Fernando Cotica, "Synthesis and Structural Studies of Core-shell Magnetoelectric Nanoparticles," Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Ruyan Guo, Robert A. McIntosh, Michael Miller, Amar S. Bhalla, "Electrical, Optical, and Mechanical Coupled Phenomena in Ferroelectric Materials near Piezoelectric Resonance," Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Soutik Betal, Ruyan Guo, Amar Bhalla, Kelly Nash, Moumita Dutta, Edward Khachatryan, Luiz Fernando Cotica, "Magnetoelectric Emission by Core-shell Magneto-electric Nanoparticles,"(2015)Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Juan P. Tamez, M.C. Bhardwaj, Amar Bhalla, Ruyan Guo, "Design and Simulation of TriPhasic PZT Piezoelectric Transducers", University Park, PA. (May 2015) International Workshop on Acoustic Transduction Materials and Devices, State College, PA.

A. J. Mincache, O. G. Oliveira, D. M. Silva, I. A. Santos, L. F. Cótica, R. Guo, A. S. Bhalla, "Study of magnetoelectric coupling in BiNdFeCoO3 compositions using ferroic characterizations", Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

B. C. F. Farinelli, E. R. Botero, C. T. Carvalho, R. Guo, A. S. Bhalla and E. A. Falcão, "Synthesis and spectroscopic studies of Poly (¿uoride) of vinylidene ferroelectric ¿lms", Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

D. S. F. Viana, F. P. Milton, K. R. C. P. Jimemez, A. J. Gualdi, P. C. Camargo, A. J. A. Oliveira, J. A. Eiras, A.S . Bhalla, R. Guo, D. Garcia, "Ferroic properties of 0.675[PbMg1/3Nb2/3O3] - 0.325[PbTiO3]/CoFe2O4 composites prepared by Spark Plasma Sintering", Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

G. G. Leite, E. R. Botero, C. T. Carvalho, R. Guo, A. S. Bhalla, and E. A. Falcão, "Synthesis and Characterization of Er3+ Doped Polyvinylidene Fluoride Samples", Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

G. M. Santos, I. B. Catellani, B. F. Oliveira, I. A. Santos, R. Guo, A. S. Bhalla and L. F. Cótica, "Theoretical & Experimental Studies of the Structure of AlFeO3 Compositions," Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

I. B. Catellani, G. M. Santos, B. F. Oliveira, G. S. Dias, I. A. Santos, L. F. Cótica, R. Guo, A. S. Bhalla, "Ab initio calculations and Maximum Entropy Method Applied to the Study of BiFeO3 structure. I. B. Catellani1, G. M. Santos1, B. F. Oliveira1, G. S. Dias1, I. A. Santos1, L. F. Cótica1, R. Guo2, A. S. Bhalla2," Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

M. Dutta, S. Betal, X. G. Peralta, A. S. Bhalla and R. Guo, "Nanoscopic ¿eld dependent material study probed by THz pulses," Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

M. S. Silva, B. C. F. Farinelli, E. R. Botero, C. T. Carvalho, R. Guo, A. S. Bhalla and E. A. Falcão, "Studying optical properties of

AMT/Eu2O3 doped PVDF samples," Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

P. N. Oliveira, D. Alanis, R. D. Bini, D. M. Silva, G. S. Dias, I. A. Santos, S. Betal, R. Guo, A. S. Bhalla, L. F. Cótica, "Biological applications of ferroic nanoparticles," Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

S. Betal, M. Dutta, B. Shrestha, E. Khachatryan, L. F. Cótica, L. Tang, K. Nash, A. S. Bhalla and R. Guo, "Magneto-Elasto-Electroporation (MEEP) – In-vitro Visualization & Numerical Characterization," Second International Workshop on Advances in Multifunctional Multiferroic Materials and Their Applications & 2015 INAMM Meeting, CNPq and NSF, (August 2015)Maringa, Brazil.

Aref Asghari; Ruyan Guo ; Amar Bhalla, "An Investigation and Characterization of Liquid Water and Ice Crystal Mixture at Microwave using Cavity Perturbation Technique". Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Guilherme Santos; Breno Oliveira; Gustavo Dias; Igor Catellani; Ivair Santos; Ruyan Guo; Amar Bhalla; Luiz Cótica, "Theorical & Experimental Structural and Magnetoelectric effect in AlFeO3 Compositions" Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Idalci Cruvinel dos Reis; Atair Carvalho da Silva; Ruyan Guo; Amar Bhalla; Jose de Los Santos Guerra, "Raman Scattering and Dielectric Properties of Bi-layered SrBi2Ta2O9 Aurivillius' Ferroelectric Ceramics". Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Igor Catellani; Breno Oliveira; Ivair Santos; Ruyan Guo; Amar Bhalla; Luiz Cotica, "Theoretical and Experimental Studies in Chemical Bonding in BiFeO3-based Compositions". Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Jose de Los Santos Guerra; Atair Carvalho da Silva; Idalci Cruvinel dos Reis; Soutik Betal; Moumita Dutta; Adilson Jesus Aparecido de Oliveira; Ruyan Guo; Amar Bhalla "Room Temperature Ferroic Responses in PZT/Ni-ferrite Based Ceramic Composites". Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Marco Aurélio de Oliveira; Ruyan Guo; Amar Bhalla; Jose de Los Santos Guerra, " Investigation of the Structural Properties of A- and B-site Modified BaTiO3 Ferroelectric Ceramics". Symposium of Advances in Dielectric Materials and Electronic Devices, Materials Science & Technology 2015, Oct. 4-8, 2015, Columbus, Ohio.

Ruyan Guo, Robert A. McIntosh, M. Tanvir Hasan, Carol EllisTerrel, Michael Miller, and Amar S. Bhalla, "Numerical Investigation of Electrical, Optical, and Mechanical Coupled Phenomena Influenced by Piezoelectric Resonances",2015 International Workshop on Acoustic Transduction Materials and Devices, University Park, PA. (May 2015).

Number of Presentations: 25.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
05/30/2016	35.00 Shizhuo Yin, Ruyan Guo, Md. Tanvir Hasan, Amar Bhalla, Ruyan Guo. Investigation of electrical, optical and structural properties of sputtered indium tin oxide thin film, SPIE Optical Engineering + Applications. 09-AUG-15, San Diego, California, United States. : ,
07/02/2014	13.00 Robert McIntosh, Amar Bhalla, Ruyan Guo, Shizhuo Yin, Ruyan Guo. Time domain modeling of induced birefringence and phase shift in piezoelectric resonance enhanced electro-optic modulators, SPIE Optical Engineering + Applications. 25-AUG-13, San Diego, California, United States. : ,
09/08/2013	5.00 R. McIntosh, A. S. Bhalla, R. Guo. Simulation of enhanced optical transmission in piezoelctric materials, Advances and Applications in Electroceramics II - Materials Science and Technology Conference and Exhibition; Columbus, OH, United states, 2012, pp. 55-64. . 16-OCT-12, . : ,
09/09/2013	7.00 Robert McIntosh, Amar S. Bhalla, Ruyan Guo. Time domain modeling of induced birefringence and phase shift in piezoelectric resonance enhanced electrooptic modulators, Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VIII. 25-AUG-13, . : ,
09/24/2012	1.00 R. McIntosh, A. S. Bhalla, R. Guo. Finite element modeling of acousto-optic effect and optimization of the figure of merit, Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VI, Conference 8497 August 2012, San Diego, CA (in printing).. 13-AUG-12, . : ,
10/16/2015	21.00 Md. Shafiqur Rahman, Carlos D. Garcia, Amar Bhalla, Ruyan Guo. Optical characterization of ferroelectric PZT thin films by variable angle spectroscopic ellipsometry, SPIE Optical Engineering + Applications. , San Diego, California, United States. : ,
10/16/2015	22.00 Robert McIntosh, Amar S. Bhalla, Ruyan Guo. Vibrometry analysis of electrooptical coupling near piezoelectric resonance, SPIE Optical Engineering + Applications. , San Diego, California, United States. : ,
10/16/2015	23.00 Keith Delahoussaye, Ruyan Guo, Amar Bhalla. Homodyne and heterodyne optical interferometry for frequency dependent piezoelectric displacement measurement, SPIE Optical Engineering + Applications. , San Diego, California, United States. : ,
10/16/2015	25.00 Moumita Dutta, Carol Ellis, Xomalin G. Peralta, Amar Bhalla, Ruyan Guo. Terahertz electrical and optical properties of LiNbO, SPIE Optical Engineering + Applications. , San Diego, California, United States. : ,
10/16/2015	26.00 Md. Tanvir Hasan, Amar Bhalla, Ruyan Guo. Investigation of electrical, optical and structural properties of sputtered indium tin oxide thin film, SPIE Optical Engineering + Applications. , San Diego, California, United States. : ,

TOTAL: 10

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
09/02/2014	16.00	Juan P. Tamez, M.C. Bhardwaj, Amar Bhalla, Ruyan Guo. Simulation and Experimental Studies on Tri-Phasic PZT piezoelectric Transducer, Ferroelectrics (05 2014)
09/02/2014	17.00	R. MCINTOSH, A. S. BHALLA, RUYAN GUO. Modulating Frequency and Responsivity of Pyroelectric Energy Converters by Finite Element Analysis, Ferroelectrics (07 2014)
10/19/2015	31.00	Melissa Montes, Christopher G. Pierce, Jose L. Lopez-Ribot, Amar S. Bhalla, Ruyan Guo. Properties of Silver and Copper Nanoparticle-Containing AqueousSolutions and Evaluation of their In Vitro Activity againstCandida albicans and Staphylococcus aureus Biofilms, Nano Research (08 2015)
TOTAL:		**3**

Number of Manuscripts:

Books

Received		Book
09/01/2014	14.00	Shizhuo Yin, Ruyan Guo. Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VII, Bellingham, Washington 98227-0010 USA: SPIE Society of Photo-Optical Instrumentation Engineers ISBN: 9780819496973 , (10 2013)
09/24/2012	2.00	Shizhuo Yin, Ruyan Guo (editors). Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VI (Proceedings Volume), Seattle Washington: Proceedings of SPIE, (09 2012)
10/16/2015	24.00	Yin, S. (Ed.), Guo, Ruyan (Ed.). Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications IX, Bellingham, WA,: SPIE, Bellingham, WA, , (09 2015)
10/19/2015	29.00	S. Yin (editor), Ruyan Guo (editor). Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VIII; ISBN 978-1-6284-1227-7, Bellingham, Washington, USA: Society of Photo-Optical Instrumentation Engineers, (09 2014)
TOTAL:		**4**

Received Book Chapter

TOTAL:

Patents Submitted

[1]S. BETAL, B. SHRESTHA, M. DUTTA, K. NASH, L. TANG, A. S. BHALLA, and R. GUO, "METHODS AND COMPOSITIONS RELATED TO MAGNETO-ELASTO-ELECTROPORATION (MEEP)," 10/15/2015. 62/241,786 (provisional)

[2] Moumita Dutta, Soutik Betal, Amar Bhalla, Ruyan Guo, "Piezoelectric Resonance Controlled Millimeter Wave (Terahertz)Modulator," Tech Innovation Disclosure filed Mar. 10, 2016 (patent application pending).

Patents Awarded

Awards

Dr. Ruyan Guo (PI) received Recognition Award for serving Advisory Board for American Chemical Society Petroleum Research Fund from 2009 to 2015.

Dr. Amar Bhalla (CoPI) honored by a Special Journal Volume honoring life Career Achievement (Ferroelectrics Volume 470, Oct. 2014)

Dr. Guo (PI) invited to be a Visiting Professor: EPFL (Swiss Federal Institute of Technology in Lausanne), Lausanne, Switzerland (July-Aug., 2015), Swiss Federal Institute of Technology in Lausanne.

Dr. Guo (PI) honored as Fellow of the Institute of Electrical and Electronics Engineers (IEEE), 2013

Dr. Guo (PI) receives College of Engineering Faculty Award for Excellence in Research, UTSA, 2013

Students Recognitions (in 2015-2016):

•Presidential Dissertation Fellowship Award - Moumita Dutta
•Presidential Dissertation Fellowship Award - Soutik Betal
•Materials Research Graduate Fellowship Award - Ramya Vadlamani
•SPIE Graduate Student Travel Award - Moumita Dutta
•SPIE Graduate Student Travel Award - Soutik Betal
•Panama Governmental Fellowship Award (IFARHU- SENACYT Panama) - Melissa Montes
•Outstanding Graduate Research Award for Doctoral Research – Madhuparna Pal

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Chance Rabun	0.50	
Moumita Dutta	0.50	
Soutik Betal	0.50	
Juan Tamez	0.25	
S. R. Vadlamani	0.10	
M. M. Montes Aguirre	0.10	
S. M. Malladi	0.10	
F. A. Chowdhury	0.25	
FTE Equivalent:	**2.30**	
Total Number:	**8**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Ruyan Guo	0.15	
Amar S Bhalla	0.25	
Michael Miller (SwRI, Special mem	0.00	
FTE Equivalent:	**0.40**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Brady Emokpae	0.00	BS Computer Engineering
Steven Rosas	0.00	BS Computer Engineering
Brandon Philpot	0.25	BS Electrical Engineering
Raymundo Salazar	0.25	BS Electrical Engineering
Max Estrada	0.00	BS Mechanical Engineering
George Nall	0.00	BS Mechanical Engineering
FTE Equivalent:	**0.50**	
Total Number:	**6**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 2.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 2.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 2.00

Names of Personnel receiving masters degrees

NAME
Melissa Montes
F. A. Chowdhury
S. M. Malladi
S. R. Vadlamani
Total Number: 4

Names of personnel receiving PHDs

NAME
Soutik Betal (fall 2016)
Juan Tamez (fall 2016)
Moumita Dutta (2017)
Robert McIntosh (PhD 2014)
Total Number: 4

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

5 **METHODS AND COMPOSITIONS RELATED TO MAGNETO-ELASTO-ELECTROPORATION (MEEP)**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) Y

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2): US and International patent pending (10/15/2015)

5a: S. BETAL, B. SHRESTHA, M. DUTTA, K. NASH, L.

5f-1a: The University of Texas at San Antonio

5f-c: One UTSA Circle

San Antonio TX 78249

5 **Piezoelectric Resonance Controlled Millimeter Wave (Terahertz) Modulator**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Moumita Dutta, Soutik Betal, Amar Bhalla, and Ruyan

5f-1a: The University of Texas at San Antonio

5f-c: One UTSA Circle

San Antonio tx 78249

Scientific Progress

(see attachment)

Technology Transfer

Collaborating with private industry (Ultran Group) on designing and characterization of low frequency 100kHz and 200kHz piezo tri-phasic composite transducers for non-destructive evaluation.

RESEARCH PROJECT SUMMARY ATTACHMENT

TECHNICAL SUMMARY ATTACHMENT
#W911NF-12-1-0082
PI: Ruyan Guo (UTSA)

Innovative Electro-mechanical Transduction Mechanisms and Applications:
PIEZOELECTRIC RESONANCE DEFINED HIGH PERFORMANCE SENSORS AND MODULATORS

SUMMARY

The objectives of this research have been (1) to explore mechanisms of nonlinear electro-mechanical-optoelectronic coupling processes at multiple frequencies defined by piezoelectric resonances and (2) to develop a family of novel frequency-selective devices of exceptional properties, such as ultralow power microwave sensors and ultrafast/ultra-compact photonic modulators. The research approach adopted was to study the principles governing the polarization and lattice-phonon coupled phenomena at resonance using finite element analysis modeling and by conducting a series of carefully designed electrooptic and microwave-photonic experiments on piezoelectric resonators.

The Scientific Significance: The combined numerical and experimental investigations revealed the defining parameters of the resonance process, which combines contributions of the strain gradient, the local polarization, and the displacement current in ferroelectric piezoelectric crystal-resonator. The project conducted led to an essential understanding of the nonlinear multi-physics coupling process at resonance and the development of engineering strategies that capture the substantial potential of the piezoelectric resonance defined electromagnetic interconnecting devices.

The Educational Significance: The project is interdisciplinary requiring a broad range of knowledge including solid state physics, material science, and electrical engineering. It thus provided excellent research and education/training opportunities for undergraduate and graduate students. The PI and the research team have attracted and mentored both undergraduate/graduate and underrepresented STEM students in research. The project helped the development of engineering laboratory courses and strengthened the new interdisciplinary graduate program in materials engineering at UTSA. The University of Texas is a Hispanic-serving-institute with a fast growing engineering research program and a rich pool of underrepresented minority students, this program brought rich educational and research opportunities to the students.

The Defense Relevance: The project conducted has close relevance to DoD/ARO/ONR especially for the Electronic and Optical Ceramics Program. Scientific advancement in

understanding and utilization of electromechanical transduction mechanisms provides potentially the Army and the Navy new family of devices of low power consumption and with unprecedented sensitivity at GHz frequencies.

II. TECHNICAL APPROACH

The Project has adopted the following approaches:
(1) Investigating and understanding mechanisms of piezoelectric-resonance-defined electrooptic (EO) amplification and frequency selective optical transmission processes;
(2) Exploring the coupling between Surface Plasmon Polaritons (SPPs), which have been elicited by frequency-selective optical transmission, and adsorbed molecules in vibrational or electronic resonance with the localized, highly attenuated electromagnetic field of the SPP; and
(3) Design and explore a family of novel frequency-selective devices of exceptional properties, such as ultralow power microwave sensors and ultrafast/ultracompact photonic modulators. The research approach is to study the principles governing the polarization and lattice-phonon coupled phenomena at resonance using finite element analysis modeling and by conducting a series of carefully designed electrooptic and microwave-photonic experiments on piezoelectric resonators.

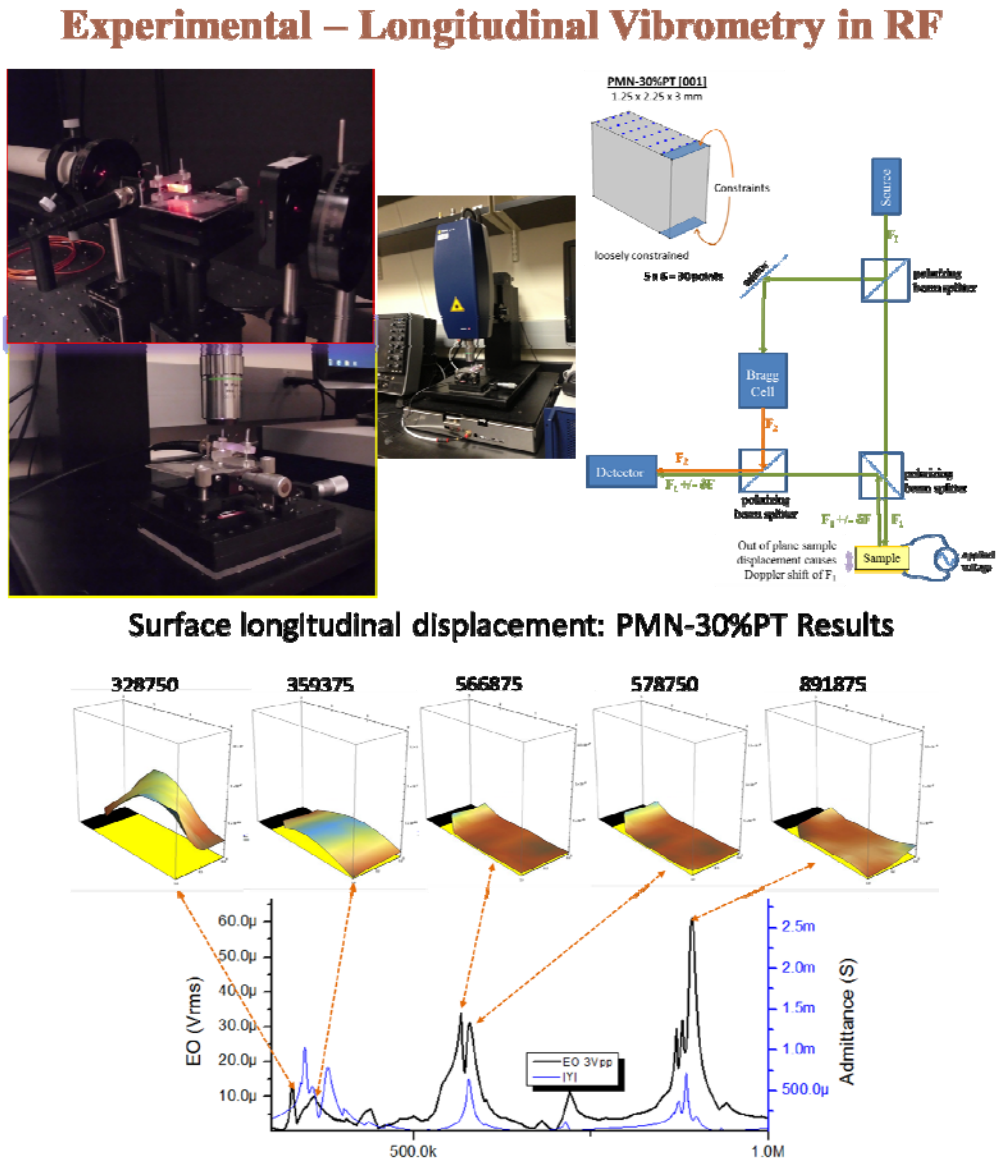
III. SUMMARY OF THE MOST IMPORTANT RESULTS

III.1. The project explored and demonstrated a wide array of methods for enhancement of sensitivity in electro-optic devices and increased electromechanical coupling in electromechanical transductions. Piezoelectric resonance enhancement has implications far beyond the implementation of electro-optic modulators operated at low frequency vibration modes. Synchronization of acoustic phonon with optical photons can open significant potential for low voltage, high sensitivity devices with wide bandwidth operation. Doctoral student Robert McIntosh has performed an extensive array of numerical and experimental research to study and further develop the subject of piezoelectric resonance enhanced electro-acoustic-optic process, in order to improve the sensitivity and efficiency of electro-optic sensors and to explore novel applications. Many finite element models have been constructed for evaluating the mechanisms of the phenomena and the effectiveness of the device structure. The enhancement in transmission is found to be directly related to the strain-coupled local polarization. At piezoelectric resonance oscillating dipoles or local polarizations become periodic in the material and have the greatest impact on transmission. Results suggest that the induced charge distribution by a piezoelectric material at certain resonant frequencies is effective for aiding or impeding the transmission of a propagating wave. The behavior of both piezoelectric-defined (or intrinsic piezoelectric materials) and engineered periodic

structures are reported. The piezoelectric response of the surface displacement of samples is investigated using an ultra-high frequency laser Doppler vibrometer. A two dimensional view of the surface is obtained and the surface displacement, velocity and acceleration are compared to the electro-optic response under the resonant condition. A study of the acousto-optic (AO) effect in a family of oxide crystals (including e.g., TiO 2 , ZnO, LiNbO3 , and ferroelectric perovskites) has been conducted by the finite element analysis method. This study further serves to show the potential of optimizing devices through a consideration of their directional dependent parameters and resonant behavior. The acousto-optic figure of merit (FOM) as a function of the material's refractive index, density, effective AO coefficient and the velocity of the acoustic wave in the material, is also investigated. By examining the directional dependent velocity, acousto-optic coefficients, and refractive index, the acousto-optic FOM can be calculated and plotted in all directions revealing the optimal crystal orientation to maximize coupling between the optical and acoustic waves. A finite element model was developed to corroborate the improved interaction. The model examines the diffraction that occurs on the optical wave as it travels through an acousto-optic medium. The combined information gained from commercially available multiphysics-based modeling platforms is shown to be an effective means of predicating acousto-optic device functionality.

R. McIntosh, "Piezoelectric resonance enhanced microwave and optoelectronic interactive devices," ProQuest, UMI Dissertations Publishing, 2013, ISBN 9781303113581, pp.184.

III.2. A holistic experimental and numerical study combining resonance impedance spectrum, EO effect and surface displacement of piezoelectric resonator as function of frequency showed the piezo enhanced effect persists and remains significant in high frequency. The capability of a high frequency vibrometer measurement, which was made available through this grant, enabled us to measure directly the surface displacement as function of the frequency. The longitudinal displacement values revealed the complex nature of the samples vibration. The high frequency displacement has been shown to decrease as the crystal becomes more constrained while the electro-optic signal remained relatively high. The acceleration of the sample surface gives a similar response showing strong peaks even when the displacement has decreased. This gives an interesting perspective suggesting that the acceleration plays a significant role in enhancement leading to further investigation for device applications.



R. McIntosh, A. S. Bhalla, and R. Guo, "Vibrometry Analysis of electrooptical coupling near piezoelectric resonance," in *Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VIII, August 17, 2014 - August 18, 2014*, San Diego, CA, United states, 2014, pp. The Society of Photo-Optical Instrumentation Engineers (SPIE).

K. Delahoussaye, R. Guo, and A. Bhalla, "Homodyne and heterodyne optical interferometry for frequency dependent piezoelectric displacement measurement," in *Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VIII, August 17, 2014 - August 18, 2014*, San Diego, CA, United states, 2014, pp. The Society of Photo-Optical Instrumentation Engineers (SPIE).

III.3. <u>Time domain finite element models were constructed to determine the phase shift</u> due to the induced birefringence of the device. Two sinusoidal voltage sources are used one to sweep over a range of frequencies while the other setting the modulator at a

selected resonance frequency. Ferroelectric single crystals such as LiNb03 and Pb(Zn1/3Nb2/3)03-PbTi03, were examined for their induced index of refraction, the induced phase shift, and the half-wave voltage of given configurations. The time domain model of dual signal ac biased configuration displayed wide bandwidth enhancement when biased at proper resonant modes, which matches well with experimental observations. The results demonstrate the piezo-resonant enhancement in terms of low half wave voltage and high electrooptic coefficients in broad frequency ranges. The results also provided corresponding insights that further our understanding on experimental observations reported previously by the authors. The models are suitable for designing electrooptic device configurations that optimize the properties desired.

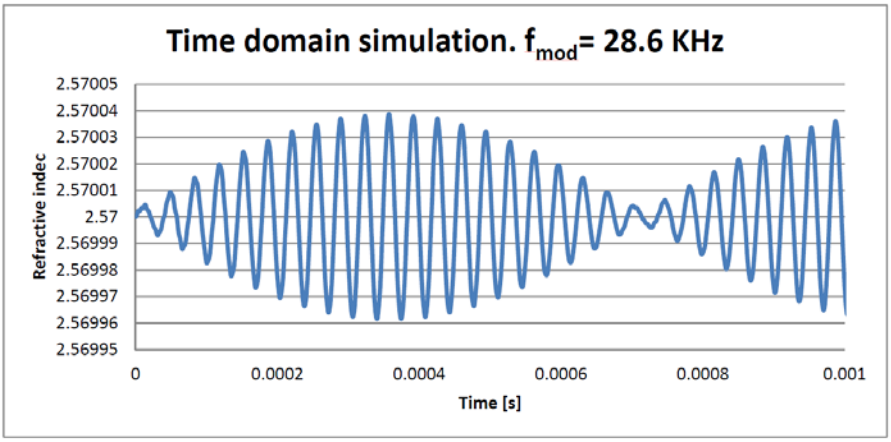


Figure 2. FEA time domain simulation of electro-optic modulator showing additional modulation near resonance.

R. McIntosh, A. Bhalla, and R. Guo, "Time domain modeling of induced birefringence and phase shift in piezoelectric resonance enhanced electrooptic modulators," in *Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VII, 25-26 Aug. 2013*, USA, 2013, p. 88471N (7 pp.).

McIntosh, R., Garcia, C., Bhalla, A., and Guo, R.Y.: 'Periodically Poled Structure on Microwave Transmissions Evaluated by Scattering Parameters', *Integrated Ferroelectrics*, 2011, **131**, pp. 219-229

III.4. In addition to resonant effects the **acousto-optic interaction was studied to facilitate a novel solution to optimized efficient sensors.** Optimizing AO devices is more than just the photoelastic relationship; this work has displayed the formation of pertinent material parameters and equations for identifying the maximum interaction directions for materials of any point group symmetry. The maximum interaction directions were shown to not always be along the Cartesian principle axes. These maximum directions typically occur where the acoustic velocity is minimized and the refractive index is maximized (yielding minimum light velocity), the longer the two waves take to co-propagate in the material the more they interact and couple. The Finite Element model of acousto-optic effect and maximum interaction directions found by the

Figure of Merit model give consistent conclusions. This work has been published in SPIE proceedings "Finite Element Modeling of Acoustooptic Effect and Optimization of the Figure of Merit", Oct. 2012. Recently the work has been extended to pyroelectric energy conversion device, using finite element model, combined with SPICE model to simulate frequency responses of energy conversion for a ferroelectric material subjected to periodic heat source.

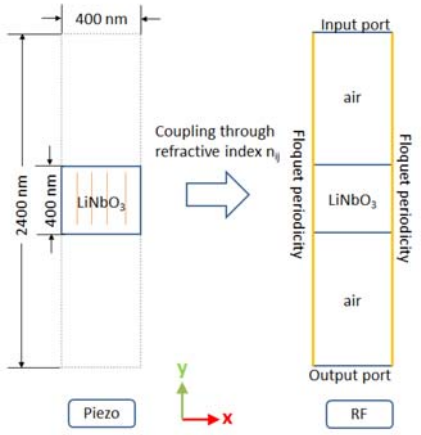


Figure 6. The setup of the piezoelectric and electromagnetic domains for the Comsol model.

R. McIntosh, A. Bhalla, and R. Guo, "Finite element modeling of acoustooptic effect and optimization of the figure of merit," in *Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VI, August 12, 2012 - August 13, 2012*, San Diego, CA, United states, 2012, pp. 849703-3.

McIntosh, R., Bhalla, A.S., and Guo, R.: 'Modulating frequency and responsivity of pyroelectric energy converters by finite element analysis', *Ferroelectrics*, 2014, **472**, (1), pp. 50-58

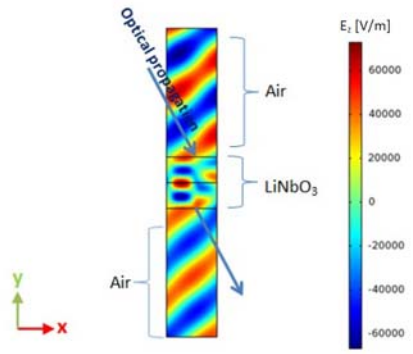


Figure 7. Comsol simulation of the optical propagation from the top section (air) into the material and to the bottom port. The z component (out of plane) of the electric field is plotted. The angle of incidence is alpha=0.7 radians.

III.5. Technical advancement has also been achieved in the area of **simulating and designing advanced tri-phasic piezoelectric composite transducers** by the combined experimental (Vibrometer) and the numerical (Finite Element Simulation COMSOL) research capabilities supported by this grant. Tri-Phase piezoelectric transducers composed of PZT-5H rods surrounded by hexagonal polymer walls in a vacuum ambient have been extensively studied by doctoral student Juan Tamez. The electrical and mechanical characteristics of these transducers are simulated and predicted. The actual transducers were fabricated through collaboration with Ultran Group. The measured piezoelectric properties of the fabricated transducer at 100 kHz corroborate with those of the predicted design. The optimized transducer design has acoustic energy channeled in the d_{33} mode at resonance, with weak or no shear mode cross-talk behavior from the other modes. The mechanical displacements measured were large and highly aligned along d_{33} mode. This implies that Tri-Phasic piezoelectric composite

transducer performs as a single device with optimized coupling coefficient and large bandwidth, one of the best performance reported in the literature for non-destructive evaluation applications (100 kHz and 200 kHz).

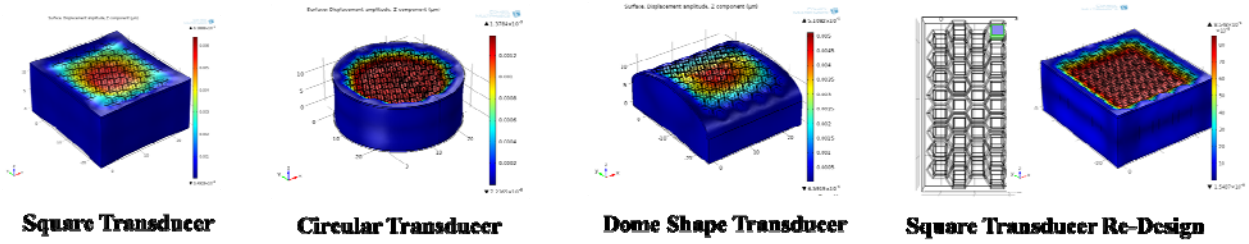


Figure 6. Three different Transducer geometries piezoelectric models at 100 kHz

Table 3
200 kHz square transducer properties from COMSOL simulation and measurement of physical transducer

	200kHz square transducer COMSOL models			Rectangular 200kHz transducer COMSOL models			Experimental transducer
	Circular rods	Hexagonal rods	Square rods	Circular rods	Hexagonal rods	Square rods	Square rods
fr (kHz)	189.95	182.95	190.30	185.05	181.9	189.95	188.00
fa (kHz)	286.90	295.3	287.95	289.00	294.25	286.9	257.00
Imp |Y| (S)	0.0188	0.00332	0.00942	0.00987	0.00639	0.01886	0.0333
Bandwidth (kHz)	96.95	112.35	97.65	103.95	112.35	96.95	69.00
Quality factor (Qm)	1.96	1.62	1.95	1.78	1.62	1.96	2.72
k_{33}	78.1%	81.4%	78.2%	79.8%	81.5%	78.1%	71.8%

J. P. Tamez, M. C. Bhardwaj, A. Bhalla, and R. Guo, "Simulation and experimental studies on tri-phasic PZT piezoelectric transducer," *Ferroelectrics*, vol. **473**, pp. 45-54, 2014.

Tamez, J.P., Bhalla, A., and Guo, R.: 'Design and simulation of 100 kHz and 200 kHz tri-phasic PZT piezoelectric transducers', *Integrated Ferroelectrics*, 2015, **166**, (1), pp. 99-107

III.VI. In related areas, the PI/CoPIs worked with international doctoral students, Yang Li and Jun Li, to explore a family of **solid solution single crystal KLTN for their exceptionally large electrooptic properties, high transition temperatures, and strong piezoelectric effect in a lead (Pb)-free composition**. Several papers are published on this topic. A rapid publication in Applied Phys. Express reported exceptionally large transverse EO r_{51} effect (11,060 pm/N), one of the highest to date. In the recent paper published in J. Appl. Phys., ("Orientation dependent electro-optic properties of $K_{0.95}Li_{0.05}Ta_{0.41}Nb_{0.59}O_3$ single crystal: Experiment and simulation"), we further reported the detailed experimental results on r_{33}, r_{13} and r_{51}. The experimental results and the crystal orientation dependent electro-optic properties were simulated based on the experimental measured electro-optic coefficients. The simulation results predicted the maximum electro-optic coefficient is to be 8548.3 pm/N and occurred at 54.53-degree away from [001] direction. In addition to the high ferroelectric phase transition

temperature (-430 K), good piezoelectric properties and high optical crystal quality, the ultrahigh electro-optic properties of $K_{0.95}Li_{0.05}Ta_{0.41}Nb_{0.59}O_3$ single crystal forecasts its outstanding potential in various electro-mechanical-optical coupled applications.

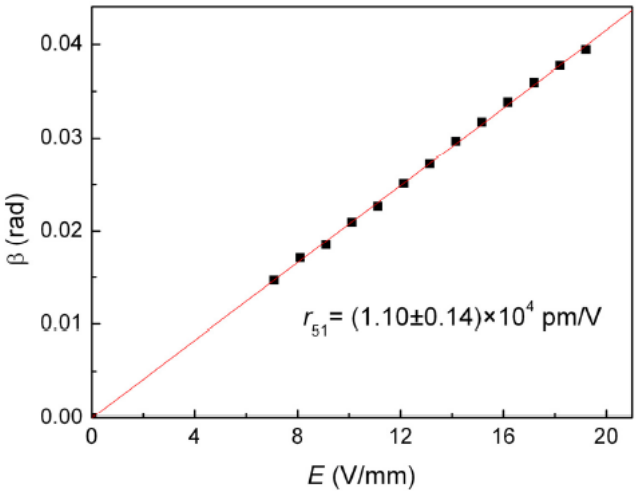


Fig. 4. Rotation of the optic axis as a function of the modulating electric field in the 0.60: KLTN single crystal.

Table 1. Electrooptic coefficients (r_{51}) of some electrooptic single crystals

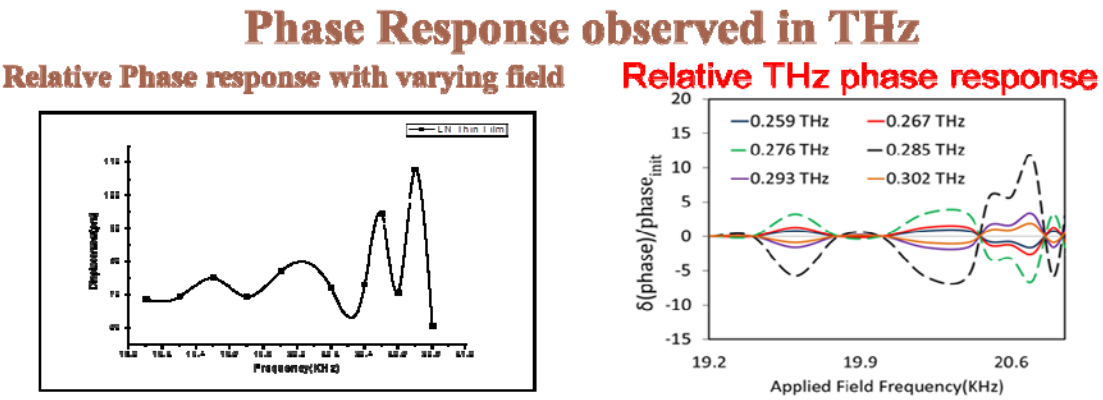
Composition	r_{51} (pm/V)
$K_{0.95}Li_{0.05}Ta_{0.40}Nb_{0.60}O_3$	$(1.10 \pm 0.14) \times 10^4$ (this work)
$BaTiO_3$	1300~1650 [12]
$KTa_{0.48}Nb_{0.52}O_3$	7850 ± 1550 [16]
$KTa_{0.53}Nb_{0.47}O_3$	5770 ± 1150 [16]
$KNbO_3$	105 [17]
$LiNbO_3$	28 [18]
SBN61	42 [19]

J. Li, Y. Li, Z. Zhou, R. Guo, and A. S. Bhalla, "Orientation dependence of dielectric and piezoelectric properties of (K0.95Li0.05) (Ta0.40Nb0.60) O3 single crystal," *Ceramics International,* vol. **41**, pp. 6657-6662, 2015.

J. Li, Y. Li, Z. Zhou, R. Guo, and A. Bhalla, "Pyroelectric properties of lead-free ferroelectric niobium-rich potassium lithium tantalate niobate single crystals," *Ceramics International,* vol. **39**, pp. 8517-8519, 2013.

J. Li, Y. Li, Z. Zhou, A. Bhalla, and R. Guo, "Linear electrooptic coefficient r51 of tetragonal potassium lithium tantalate niobate K0.95Li0.05Ta0.40Nb0.60O3 single crystal," *Optical Materials Express,* vol. **3**, pp. 2063-2071, 2013/12/01 2013.

III.7. Piezoelectric resonance modulated THz wave propagation: For the purpose of developing efficient THz modulators, this project has conducted extensive literature survey and experimental evaluations of oxide materials for their application potential in the terahertz frequency range by studying various classes of materials and categorize them based on applications. Very recently, Moumita Dutta, doctoral student supported partially by this grant, explored THz frequency behavior of single crystal LiNbO3 films, and discovered the phase modulation property influenced by piezoelectric resonance at fundamental resonance frequency. The influence of periodic gradient structure on the enhancement of microwave transmission was also predicted in this research. This work is significant as it is a direct and likely the first evidence of dynamic control of parametric amplification by piezoelectric resonance. This work is the base for a recent technical invention disclosure being filed at this time.



Dutta, M., Peralta, X.G., Bhalla, A., and Guo, R.: 'Current status of oxide dielectric materials for terahertz applications-an overview', *Integrated Ferroelectrics*, 2015, **166**, (1), pp. 108-139

Dutta, M., Ellis, C., Peralta, X.G., Bhalla, A., and Guo, R.: 'Terahertz electrical and optical properties of LiNbO3single crystal thin films', in: Conference Proceedings (SPIE, 2015, edn.), pp. DOI: 10.1117/1112.2188933.

III.8. Piezoelectric resonance and coupled multiferroic effect of Core-Shell nanoparticles: Multiferroic behavior of magnetoelectric nanoparticles exhibiting both ferromagnetic and ferroelectric properties finds significance in various applications. Soutik Betal, doctoral student partially supported by this project, fabricated ferromagnetic-ferroelectic core shell nano particles and characterized their crystalline structure and their multiferroic properties. Nanostructure by HRSEM, ferro-magnetic behavior investigated using MFM and ferroelectric behavior revealed by PFM measurement confirmed their single-crystalline structure, corroborated the multiferroic nature of these core-shell magneto-electric nano-particle (CSMEN). Intriguingly, we found that the core-shell nanoparticles fabricated respond to applied magnetic (or electric) field differently under ac or dc conditions, and at different frequencies. It is the

ac (instead of dc) field that is necessary to excite the movement of the CSMEN to enter a giving biological cell. We are currently studying the interrelations, especially the frequency and amplitude of the modulating field in relation to the ferroelectric layer's thicknesses, etc., in order to optimize the nanoparticle piezo-magnetostriction coupled process. The research has been performed on biomedical cells and has potential to contribute to drug delivery and biomedical imaging. This work has led to a patent disclosure and a pending publication (currently after the first round of revision).

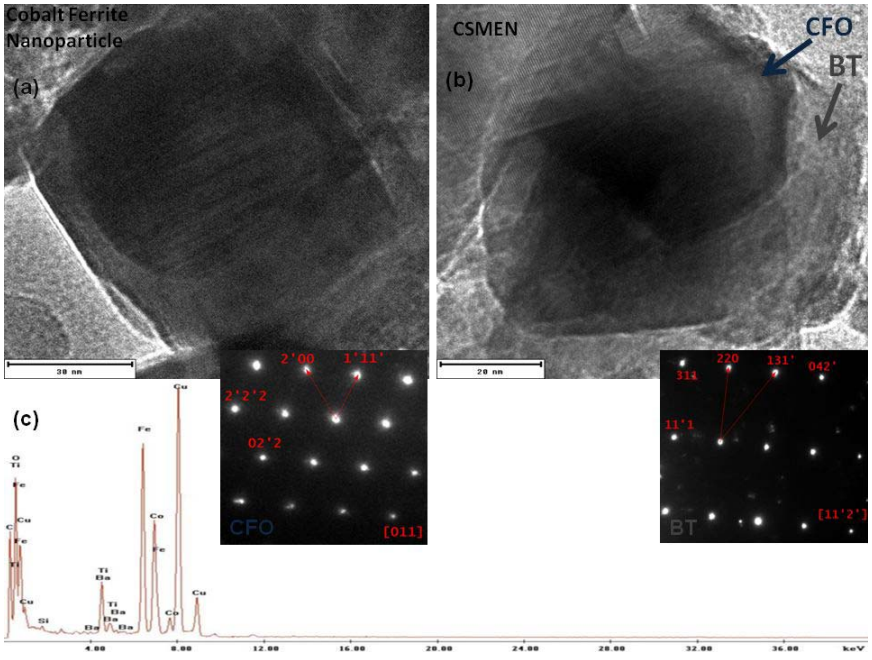


Figure 2: Morphology and microstructure of the synthesized CSMENs demonstrated by Transmission Electron Microscopy image and inset of selective area diffraction patterns (a) for the CFO core and (b) for the CSMEN's BT shell. The energy dispersive spectrum is also shown in **(c)** for the average composition of the CSMEN.

Betal, S., Dutta, M., Cotica, L.F., Bhalla, A., and Guo, R.: 'BaTiO3coated CoFe2O4-Core-Shell Magnetoelectric Nanoparticles (CSMEN) characterization', Integrated Ferroelectrics, 2015, 166, (1), pp. 225-231

S. BETAL, B. SHRESTHA, M. DUTTA, K. NASH, L. TANG, A. S. BHALLA, and R. GUO, "METHODS AND COMPOSITIONS RELATED TO MAGNETO-ELASTO-ELECTROPORATION (MEEP)," 10/15/2015. 62/241,786 (US and International patent pending).

Betal, S., Shrestha, B., Dutta, M., Coticad, L.F., Khachatryan, E., Nash, K., Tang, L., Bhalla, A.S., and Guo, R.: 'Magneto-Elasto-Electroporation (MEEP) - In-vitro visualization and numerical characteristics', *Scientific Reports*, (pending publication)

IV. TRAINING AND DEVELOPMENT PROVIDED

This project provided **training and professional development opportunities to four UTSA and two international graduate students;** three completed and three ongoing:

- Robert McIntosh completed his PhD dissertation end of 2013. He worked as a postdoctoral researcher at UTSA and then at Southwest Research Institute, one of the largest non-profit research institutes in the United States. Robert's successful doctoral research was guided by the PI/CoPIs (Guo, Bhalla, and Miller). He is now a research engineer at Corning Inc.
- Yang Li and Jun Li, international visiting students, defended their doctorate degrees in fall 2013. Jun Li is a faculty member, Assistant Professor, Department of Physics, Harbin University of Science and Technology. Yang Li is now a faculty member, Assistant Professor, Chemistry and Environmental Engineering, Harbin University of Science and Technology.
- Juan Tamez (DoD employee, Hispanic American) focuses on design (simulation and optimization) of piezoelectric transducer with tri-phasic configuration. His work continues to generate technical collaboration interests with small companies of transducer industry. He is expected to complete his PhD in spring 2016.
- Moumita Dutta, is currently doctoral candidate exploring the resonance enhanced process at millimeter wave range.
- Soutik Betal, is currently a doctoral candidate conducting multiferroic core-shell structured composite study, extending applications to biomedical applications.

This project has provided **training and professional development opportunities to Ten masters' students to date**, nine completed and two ongoing:

- **Anish Shinde** (graduated with MS spring 2012- currently working at QUALCOMM); **Sandeep Kumar Bomthapalli** (graduated in 2013, now an engineer at TRW Automotive); **Sheshidhar Reddy Kolanu** (graduated May 2013); **Md. Qumrul Hasan** (graduated May 2014, currently hired as a systems engineer by Bank One); **Keith Delahoussaye** (participated the project as an undergraduate, then graduate, and graduated in Aug. 2014, an engineer of Air Force, and currently US Patent Examiner). **Chowdhury, Fahad Abdullah** (graduated in fall 2015). **Ramya Vadlamani** (graduated in spring 2015, now employed by INTEL), **Mahuri Malladi** (graduated in spring 2015), and **Melissa Montes** (graduated in summer 2015, now working for Gov. of Panama).
- Bryan Gamboa (Hispanic American) is currently conducting MS research on optical sensing technology in remote detection of displacement.

- Chance Rabun (Native American) joined the project as a MS student and is conducting microwave coupled optical measurement.

This project provided **training opportunities to six undergraduate or high school students to date**:

Lab/research Assistants- **Keith Delahoussaye** (BS EE summer 2012); **Bryan Gamboa** (BS EE spring 2014 till summer 2015) had exposure to DoD research as undergraduates and then became MS students. Keith is now US Patent Examiner, Bryan is interested to pursue doctoral degree or as a future DoD employee. In the past year, **George Nall** and **Max Estrada** were interactive with the PI/CoPIs. George graduated with BS in Mechanical Engineering and now a MS student in Materials Engineering. Max graduated spring 2016 with BS in Mechanical Engineering and is interested to enter MS program in Materials Engineering fall 2016.
The PI/CoPI offered research exposure to four High School summer lab assistants, **Michael Tao** (summer 2012); **Shaneel bin Zaid** (summer 2013); **Reddhi Kumar** (summer 2013) and **Anjelina Das** (summer 2014). Reddhi Kumar has gone on to win Texas State Award for Science Exhibition, all of the high school students enrolled in colleges of their choices.

The **PI offers Dielectric Engineering Lab courses for undergraduate and graduate students**, students enrolled had hands-on experimental training. Electrooptics, microwave measurement, optical interferometry measurement are offered to the students. A wide range of research exposure and relevant skills were provided to the students.

Figure: Undergraduate students of Electrical and Computer Engineering, University of Texas at San Antonio, conducting microwave waveguide perturbation experiment (left) and laser interferometry piezoelectric displacement measurement (right), through taking Dr. Guo's Dielectric and Optoelectronic Engineering Lab course.

V. PUBLICATION LIST

(Student author underlined)

1. Betal, S., Shresth, B., Dutta, M., Cotica, L.F., Khachatryan, E., Nash, K., Tang, L., Bhalla, A.S., and Guo, R.: 'Magneto-Elasto-Electroporation (MEEP) - In-vitro visualization and numerical characteristics', *Scientific Reports* (submitted) 2016
2. Moumita Dutta, Md. Shafiqur Rahman, Amar S. Bhalla & Ruyan Guo, "Optical and microstructural characterization of multilayer Pb(Zr0.52Ti0.48)O3 thin films correlating ellipsometry and nanoscopy", *Journal of Materials Science*, **51**(15) 2016
3. Tamez, J.P., Bhalla, A., and Guo, R.: 'Design and simulation of 100 kHz and 200 kHz tri-phasic PZT piezoelectric transducers', *Integrated Ferroelectrics*, 2015, **166**, (1), pp. 99-107
4. Betal, S., Dutta, M., Cotica, L.F., Bhalla, A., and Guo, R.: 'BaTiO3coated CoFe2O4-Core-Shell Magnetoelectric Nanoparticles (CSMEN) characterization', *Integrated Ferroelectrics*, 2015, **166** (1), pp. 225-231
5. Moumita Dutta; Carol Ellis ; Xomalin G. Peralta ; Amar Bhalla ; Ruyan Guo, "Terahertz electrical and optical properties of LiNbO3 single crystal thin films," *Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications IX,* SPIE proceedings 9586 (2015)
6. M. T. Hasan, A. Bhalla, and R. Guo, "Investigation of electrical, optical and structural properties of sputtered indium Tin Oxide thin film," in *Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications IX*, August 9, 2015 - August 10, 2015, San Diego, CA, United states, 2015, p. DOI:10.1117/12.2188971.
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9. K. Delahoussaye, R. Guo, and A. Bhalla, "Homodyne and heterodyne optical interferometry for frequency dependent piezoelectric displacement measurement," in *Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VIII, August 17, 2014 - August 18, 2014*, San Diego, CA, United states, 2014, pp. The Society of Photo-Optical Instrumentation Engineers (SPIE).
10. R. McIntosh, A. S. Bhalla, and R. Guo, "Modulating frequency and responsivity of pyroelectric energy converters by finite element analysis," *Ferroelectrics,* vol. **472**, pp. 50-58, 2014.
11. M. S. Rahman, C. D. Garcia, A. Bhalla, and R. Guo, "Optical characterization of ferroelectric PZT thin films by variable angle spectroscopic ellipsometry," in *Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VIII,*

August 17, 2014 - August 18, 2014, San Diego, CA, United states, 2014, pp. The Society of Photo-Optical Instrumentation Engineers (SPIE).

12. R. McIntosh, A. S. Bhalla, and R. Guo, "Vibrometry Analysis of electrooptical coupling near piezoelectric resonance," in *Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VIII, August 17, 2014 - August 18, 2014*, San Diego, CA, United states, 2014, pp. The Society of Photo-Optical Instrumentation Engineers (SPIE).
13. Y. Li, J. Li, Z. Zhou, R. Guo, and A. S. Bhalla, "Electrical Properties of Lead-free Fe-doped Niobium-rich Potassium Lithium Tantalate Niobate Single Crystals," *Europhysics Letters*, vol. **104**, p. 57008 (6 pp.), 12/ 2013.
14. J. Li, Y. Li, Z. Zhou, A. Bhalla, and R. Guo, "Linear electrooptic coefficient r51 of tetragonal potassium lithium tantalate niobate K0.95Li0.05Ta0.40Nb0.60O3 single crystal," *Optical Materials Express*, vol. **3**, pp. 2063-2071, 2013/12/01 2013.
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